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SOIL THERMAL PROPERTIES:

AN ANNOTATED BIBLIOGRAPHY

by

Alec Peters
Norman Gentieu

Prepared under

Contract No. OCD-OS-62-58
FIL No. 18G-81929

Sponsored by

OFFICE OF CIVIL DEFENSE
Washington, D.C.

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The Franklin Institute, Phila., Pa.
October, 1962

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INTRODUCTION

This annotated bibliography is the result of a literature search undertaken by the Franklin Institute's Science Information Service as a part of the research contract No. OCD-OS-62-58 "Thermal Study of Underground Air Ducts." The research was sponsored by the Office of Civil Defense, Washington, D. C., and carried out by the Franklin Institute's Nuclear Systems Laboratory. The objective of the project was "A detailed study of the effect of underground ventilating ducts in minimizing variations in shelter atmosphere temperature due to seasonal, diurnal and brief but extreme changes in above-ground temperature. The performance of this study entails a combination of theoretical, analytical-computational, model

and full-scale experimental investigations."

Appropriate journals, technical reports, symposia, and Doctoral Dissertations in the fields of soil science and thermophysical properties were checked for papers relating to the thermal properties and moisture content of soils, and the measurement thereof, as related to the above problem. With very few exceptions the selection of papers was limited to applications and conditions in continental United States and Canada. The annotations were derived from authors' abstracts, Meteorological and Geoastrophysical Abstracts, Chemical Abstracts, Nuclear Science Abstracts, and U. S. Government Research Reports. In many cases the annotations were prepared by the compilers of this survey.

The references are chronologically arranged under four major headings: Measurement Techniques, Thermal Properties, Moisture, and Design of Underground Structures.

A detailed Subject Index and an Author Index are provided for the convenience of the reader.

No claim is made as to the all-inclusiveness of this bibliography, but the references are deemed to provide adequate background information for investigating the use of

buried ducts to control the temperature of air supplied to fallout shelters.

MEASUREMENT TECHNIQUES

momentary currents of 0.02 amp. Moisture determinations are based on the heating effect of passage of a constant current of 0.1-0.4 amp. through R_4 until equilibrium is reached between heat input and dissipation in the soil. In practice, readings are made at some selected time interval (60 sec. or less) after the heating current is applied. A calibration curve based on time interval and applied current must be made for each soil. The readings are not influenced by external temperature or the salt concentration of the soil solution.

3. HEAT CONDUCTIVITY AS AN INDEX OF SOIL MOISTURE. Shaw, B. and L. D. Baver, J. Am. Soc. Agron., Vol. 31, Pp. 886-891(1939)

A diagram and description are given of an adaptation of the Wheatstone bridge for measuring the changes in heat conductivity of a soil at varying moisture contents. Heat conductivity gives a reliable index of the moisture content of the soil. Changes in salt concentration of the soil solution do not materially affect the heat conductivity of the soil.

4. A STUDY OF METHODS OF MEASURING SOIL PRESSURES AND THEIR RELATION TO SOIL PROPERTIES. Osterberg, J. O., Doctoral Dissertation, Cornell University, (1940).

(Not seen)

momentary currents of 0.02 amp. Moisture determinations are based on the heating effect of passage of a constant current of 0.1-0.4 amp. through R_4 until equilibrium is reached between heat input and dissipation in the soil. In practice, readings are made at some selected time interval (60 sec. or less) after the heating current is applied. A calibration curve based on time interval and applied current must be made for each soil. The readings are not influenced by external temperature or the salt concentration of the soil solution.

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4. A STUDY OF METHODS OF MEASURING SOIL PRESSURES AND THEIR RELATION TO SOIL PROPERTIES. Osterberg, J. O., Doctoral Dissertation, Cornell University, (1940).

(Not seen)

5. APPARATUS FOR DETERMINATION OF THE THERMAL CONDUCTIVITY OF SOILS. Romanovsky, V., Compt. Rend., Vol. 213, Pp. 584-586, (1941)

An apparatus is described and illustrated for determining the thermal conductivity of soils. Generalizations are made relative to effects of soil continuity and liquid medium.

6. THE MOISTURE POTENTIAL OF SOILS BY THE CRYOSCOPIC METHOD. Marshall, T. J., Doctoral Dissertation, Univ. of California, (1941)

(Not seen)

7. IMPROVEMENTS IN THE PLASTER OF PARIS ABSORPTION BLOCK RESISTANCE METHOD FOR MEASURING SOIL MOISTURE UNDER FIELD CONDITIONS. Bouyoucos, G. J. and A. H. Mick, Soil Science, Vol. 63, Pp. 455-465, (1947)

The range of the technique of measuring soil moisture by observing the resistance of plaster of Paris absorption blocks is shown graphically to correspond with the amount of moisture between the permanent wilting point and the moisture equivalent. In practice the amount of H_2O remaining in the soil at a block resistance of 75,000 ohms corresponds to the amount at permanent wilt. The amount of H_2O in a surface sample of Shelby silt loam at the permanent wilting point, determined by the dilatometer method, and the amount in the sample at a block resistance of 75,000 ohms were, respectively, 12.3 and 12.5%. The moisture equivalents of a surface sample of Janesville silt loam, determined by the suction method and by measuring the amount of H_2O in

the sample when the resistance begins to increase (usually between 450 and 650 ohms) are, respectively, 23.7 and 24.0%. The circuit diagram and illustrations of an improved bridge are given.

8. TESTS FOR THERMAL DIFFUSIVITY OF GRANULAR MATERIALS. Shannon, W. L. and W. A. Wells ASTM Proceedings, Vol. 47, Pp. 1044-1054, (1947)

This paper presents the procedures, analyses, and results of tests to determine, using a simplified test procedure, the thermal diffusivity of several granular materials of types frequently used for base-course construction of highways and airports. Determinations were made with the materials in the frozen and unfrozen condition at several different unit weights and water contents. From the test data obtained, the volumetric heat capacity and the thermal conductivity for each thermal diffusivity determination were computed. The method, where used to determine the thermal conductivity, is relatively simple and inexpensive in comparison with the more precise methods generally used, yet results of tests on one material using the simplified method and a precise method compare favorably.

9. A NEW ELECTRICAL RESISTANCE THERMOMETER FOR SOIL. Bouyoucos, G. J., Soil Science, Vol. 63, No. 4, Pp. 291-298, (April 1947)

Description of a new electrical thermometer. The thermometer is simple, convenient and reliable for measuring soil temperature at various depths.

(Not seen)

10. APPARATUS FOR MEASURING THERMAL CONDUCTIVITY OF SOIL. Kersten, M. S., Proc. 2nd Int. Conf. Soil Mech. and Foundn. Engnrng, Vol. 3, Pp. 162-165, (1948)

(Not seen)

11. THE THERMAL CONDUCTIVITY OF SOILS. Kersten, M. S., Proc. Hgy. Res. Bd., Vol. 28, Pp.391-409, (1948)

Equipment and test methods used to determine the coefficient of thermal conductivity, k, of soils are described. Nineteen soils of different textures were tested at various mean temperatures, moisture contents and densities. Test values of k from 4 to 22 Btu per hr, sq ft, °F per in. were obtained. An increase in moisture above about 6-12% produces an increasingly greater conductivity for frozen soil over unfrozen. At a constant moisture content, each 1 lb per cu ft increase in soil density raises the conductivity about 3%. At constant density, an increase in moisture content increases the conductivity. Coarse textured soils have higher conductivity values than fine silts or clays. Soils containing quartz have higher conductivity values than those with basic rock materials.

12. COMPUTING SOIL TEMPERATURES. Langbein, W. B., American Geophysical Union, Transactions, Vol. 30, No. 4, Pp. 543-547, (Aug. 1949)

Description of the method for computing soil temperature from surface temperature. This method is adaptable to the irregular fluctuation in temperature ordinarily found in nature as well as to ideal cases. Bliss' data were used for comparison of observed and computed temperatures at depths up to 4 feet.

13. MEASUREMENT OF SOIL MOISTURE BY THE ELECTRICAL RESISTANCE METHOD. Bouyoucos, G. J. and G. A. Crabb, Jr., Agricultural Engineering, Vol. 30, No. 12, Pp. 581-583, (Dec., 1949)

Plaster of paris and nylon resistance elements, and modification of Wheatstone bridge known as Buoyoucos Model C resistance bridge, discussed; method consists of placing porous element within soil profile; such element, carefully selected, tends to establish relatively rapid moisture equilibrium with soil; moisture content varies directly with moisture content of soil.

14. "THE MEASUREMENT OF SOIL MOISTURE AND DENSITY BY NEUTRON AND GAMMA-RAY SCATTERING." Belcher, D. J., T. R. Cuykendall and H. S. Sack, U. S. Civil Aeronautics Admin. Tech. Development Report No. 127(1950)

A device is described for measuring soil moisture and density by lowering a radioactive radium-beryllium source and detector into a metal tube driven into the ground. Fast neutrons are converted into slow neutrons by impact with moisture. The number of slow neutrons is proportional to the water content of the soil.

15. THE MEASUREMENT OF THE THERMAL CONDUCTIVITY OF SOILS AND THE CALCULATION OF OIL TEMPERATURES IN BURIED PIPELINES. Brummage, K. G., J. Inst. Petroleum, Vol. 36, Pp. 575-92, (1950)

Several large diameter pipelines are being laid in the Middle East, and others are planned. Some will be buried. The temperature of the oil in such pipes is important for the following reasons: (1) through its effect on viscosity, it controls the throughput; (2) it is sometimes possible to cool the engines at pump-

in... tions by heat exchange with the oil being pumped, and the size of heat exhcanger depends on the oil temperature: (3) the protective coating on the pipe must be chosen to withstand the pipe temperature with deformation. The oil temperature is determined by the thermal conductivity and the temperature of the soil. Measurements on existing buried pipelines are reported for summer conditions at various places in the Middle East. The theoretical analysis is given, including allowances for the insulating effect of pipe coatings. A simple procedure of general application is described for calculating the temperature of liquid in turbulent flow in a buried pipeline and the temperature distribution in a representative hypothetical line is determined as an illustration of the method.

16. MEASUREMENT OF THE THERMAL DIFFUSIVITY OF A SOIL BY THE USE OF A HEAT PUMP. Penrod, E. B., J. Appl. Phys., Vol. 21, Pp. 425-427, (1950)

An earth heat pump was set in operation to abstract heat from soil assumed to be in thermal equilibrium. Temperature-time graphs of the anti-freeze and of the soil at distances of six, twelve and eighteen inches below the center of the anti-freeze line were plotted from experimental data. From these graphs data are obtained from which the thermal diffusivity of the soil is calculated. The soil was analyzed and found to fall in the general Casagrande classification of lean clay (CL) with low plasticity.

The average value of the thermal diffusivity of the soil was found to be 0.019 ft.^{2}hr.$^{-1}$(0.0049 cm^2 sec.$^{-1}$) for the soil at a density of 120 pounds per cubic foot.

17. SOIL MOISTURE MEASURE NT BY NEUTRON MODERATION. Van Bavel, C. H. M., Underwood and R. W. Swanson, Joint contributi stern Section, Soil and Water Management, Ameri ocket Society, New York, N. Y., and North Carolina icultural Experiment Station and Physics Dept., Raleigh, N. C.

(Undated)

18. TRANSIENT HEAT FLOW APPARATUS FOR THE DETERMINATION OF THERMAL CONDUCTIVITIES. Hooper, F. C. and F. R. Lepp, Htg. Piping and Air Cond., Vol. 22, No. 8, Pp. 129-35, (Aug. 8, 1950)

Portable instrument consisting of electrically heated probe developed and used at University of Toronto for determining within 10 min thermal conductivity of wet or dry solids; usefulness of instrument is demonstrated and precision of measurement indicated; mathematical theory developed.

19. THE DETERMINATION OF TEMPERATURE TRANSIENTS IN CABLE SYSTEMS BY MEANS OF AN ANALOGUE COMPUTER. Neher, J. H., Trans. of AIEE, vol. 70, Part II, Pp. 1361-1371, (1951)

A sufficiently accurate, nonmathematical method of solving transient heating problems in cable systems has been described which is based on the principle of electrical analogy and obtains the desired solution by means of an electrical analogue computer.

Such a computer has been designed specifically for this purpose, which is relatively simple and sufficiently small in size to be used in an engineering office.

Curves are presented representing the transient

21. "DETERMINATION OF SOIL MOISTURE BY NEUTRON SCATTERING." Gardner, Wilford and Don Kirkham, Soil Science, Vol. 73, Pp. 391-401, (1952)

It has been shown theoretically, and experimentally for five soils, that a method involving the scattering and slowing of fast neutrons by hydrogen may be used for measuring soil moisture. The method rests primarily on two considerations: first, hydrogen is, practically, the only material that will slow fast neutrons; second, hydrogen in soils is present almost entirely in the form of water.

In applying the above concepts, a fast-neutron source and a slow-neutron counter (source and counter combined into a single unit) are lowered into a small auger hole in the soil. The counting rate of neutrons which have been slowed by soil hydrogen is a measure of the moisture content.

22. DEVELOPMENT OF THE THERMAL CONDUCTIVITY PROBE. Hooper, F. C., and S. C. Chang, Htg. Piping and Air Cond., Vol. 24, No. 10, Pp. 125-9, (1952)

Application experience is reported and a newly developed chart is presented for the graphical evaluation of thermal conductivity from the probe readings. The probe is an instrument for finding the thermal conductivity of nonfluid materials in the range between very low density fibrous materials and dense moist clay. The method is based upon the fact that this probe is approximately an infinite and linear source dissipating heat at a constant rate in an infinite and homogeneous material. The chart method of solution which is given in detail greatly facilitates the computation of results.

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23. HOW TO COMPUTE THERMAL SOIL CONDUCTIVITIES. Genant, A., Htg. Piping and Air Cond., Vol. 24, No. 1, Pp. 122-3, (1952)

The mechanics of computing thermal conductivities of soils by a theory presented elsewhere are explained and illustrated. Values thus calculated are in reasonably good agreement with values measured experimentally.

24. THE MEASUREMENT OF SOIL MOISTURE AND DENSITY BY NEUTRON AND GAMMA RAY SCATTERING. Belcher, D. J., (Pp. 98-110 in A Symposium on Frost Action in Soils, Jan. 9-12, 1951). Highway Res. Board, Special Report No. 2, Washington, D. C., 1952

A device for measuring soil moisture and density by lowering a radioactive radium-beryllium source and detector into a metal tube driven into the ground which operates on the principle that fast neutrons are converted into slow neutrons by impact with the moisture. The number of slow neutrons is proportional to the water content of the soil. Theory, construction of instrument, results of tests in laboratory and field, and advantages in distant recording, adaptability and accuracy are outlined and equipment and results illustrated. Device is also cheap and safe if proper precautions are taken.

25. THE THERMAL CONDUCTIVITY PROBE. Hooper, F. C., (Pp. 57-59 in A Symposium on Frost Action in Soils, Jan. 9-12, 1951) Highway Res. Board, Special Report No. 2, Washington, D. C., 1952

The probe itself consists of an aluminum tube approximately 18 in. in length. Inside of the tube is stretched an axial constantan resistance wire which serves as a constant strength heat source. Near the center of the tube length in contact with the inner walls are the hot junctions of several thermocouples arranged in series with external cold junctions. The tube is closed by a steel tip at the lower end and the wiring carried out through a seal at the upper end.

The necessary potentiometer, battery and controls are conveniently mounted in a suitcase to make the whole portable.

26. SOME FIELD MEASUREMENTS OF SOIL TEMPERATURES IN INDIANA. Yoder, E. J., (Pp. 41-42 in A Symposium on Frost Action in Soils, Jan. 9-12, 1951) Highway Res. Board, Special Report No. 2, Washington, D. C., 1952

This report covers the results of field measurement of soil temperatures made under an asphaltic pavement. Temperature gauges which actuated automatic recording instruments were installed at various depths below the pavement.

The progression of heat waves through the soil, the depth of 32°F (mean temperature), and the depth of minimum temperatures of 32°F have been plotted against time. During the winter months measurements were made manually of depth of frost penetration, depth of snow cover, ground water fluctuations, and moisture content of the soils.

No definite conclusions have been drawn from the data

other than verification of several important facts brought out by previous investigators. It is indicated, however, that more attention should be directed towards considering minimum daily temperatures in a study of this type. Since this type of research is of necessity a long range study, the accumulation of data over a period of years is desirable in order to better correlate the factors affecting soil temperature.

27. AN ABSOLUTE METHOD OF DETERMINING THERMAL CONDUCTIVITY AND DIFFUSIVITY OF SOILS. Misener, A. D. (Pp. 51-57 in A Symposium on Frost Action in Soils, (Jan. 9-12, 1951) Highway Res. Board, Special Report No. 2, Washington, D. C., 1952

The most common methods for measurement of thermal conductivity of poor conductors, e.g., earth or insulating materials, are based on the fact that the sample is in a steady-state condition. For poor conductors this requires a long period before the heat flow through the sample becomes steady. During this period the heat source must be held constant. Prolonged heating aggravates such undesirable processes as moisture migration and changes in structure. Furthermore, the necessity of removing samples for measurement from their normal situation introduces uncertainties and experimental difficulties.

These methods have two more fundamental defects. First, steady-state measurements will give no information on thermal diffusivity, a constant equal in importance to conductivity in many heat-transfer problems. Second, the actual experimental devices, hot-plates, divided bars, etc. are calibrated by using materials of presumably known conductivity to either establish quantity heat flow or determine instrumental constants, such as contact resistance with the sample.

The method described here uses measurement during

heating or cooling, which may be taken rapidly and will give both thermal conductivity and diffusivity. The mathematics are rigorous and therefore the effect of assumptions made in the theory can be calculated. With heat sources of appropriate shape and dimensions, the measurements may be made absolute, i.e., they are independent of the particular measuring device and are not affected by the thermal properties of the materials used to cónstruct the source. The limits within which this condition is fulfilled can be calculated accurately. The method is applicable to a variety of different forms of apparatus. When a suitable form has been selected and a particular apparatus built, the necessary calculations may be made once and presented as graphs from which the desired results are read off as rapidly as readings are taken. A general description of the method is followed by two particular applications, a spherical heater buried in the material and a linear heater or probe inserted into the material.

28. DISCUSSION OF SOIL TEMPERATURES. FIELD MEASUREMENTS OF SOIL TEMPERATURES. Miller, H. H., (Pp. 60-63 in A Symposium on Frost Action in Soils, Jan. 9-12, 1951) Highway Res. Board, Special Report No. 2, Washington, D. C., 1952

Discussion of a project which began December 4, 1949, and ended December 31, 1950. Thermocouples were installed at 6, 12, 30, 42, 54 and 66 in. below the surface of the pavement. Charts are shown.

29. THE MEASUREMENT OF SOIL MOISTURE AND TEMPERATURE BY HEAT DIFFUSION TYPE MOISTURE CELL. Aldous, W. M., (Pp. 74-98 in A Symposium on Frost Action in Soils, Jan. 9-12, 1951) Highway Res. Board, Special Report No. 2, Washington, D. C., 1952

Procedure and materials employed in the development of soil moisture-temperature measuring equipment are described. The various stages of development are outlined briefly. Results obtained with the several types of cells investigated are presented.

The performance characteristics of the cell in its present state of development have been investigated through the medium of laboratory-calibration test and soil-moisture determinations. The performance of the present cell is unsatisfactory when in soil at moisture content above 15 percent by dry weight and is quite variable unless positive contact with ambient soil is initially established and maintained during readings. Future improvement in design to increase operating efficiency and simplify fabrication is briefly outlined.

30. HEAT TRANSFER AND TEMPERATURE DISTRIBUTION IN SOILS FOR TRANSIENT HEAT FLOW DUE TO CYLINDRICAL SOURCES AND SINKS. Touloukian, Y. S., J. D. Bottorf, and Thor Harsen (Pp. 147-160 in A Symposium on Frost Action in Soils, Jan.9-12, (1951) Highway Res. Board, Special Report No. 2, Washington, D. C., 1952

Several methods of solving problems of transient temperature distribution and heat flow in the earth surrounding embedded heat sources and sinks in which the temperature is suddenly changed from that of the surrounding medium to a new value and maintained at this new level are presented.

Solutions of the differential equations for the

temperature distribution and heat flow for the idealized case are evaluated in terms of dimensionless parameters. A numerical method is used in the study of the problem with real boundary conditions obtained from experimental observations. The method of electrical analogy is also presented as a rapid and accurate means of solving this problem. The thermal recovery (recuperation time) of the thermally disturbed soil is also studied and results shown.

31. NUCLEAR METERS FOR MEASURING SOIL DENSITY AND MOISTURE IN THIN SURFACE LAYERS. Belcher, D. J., Cuykendall, T. R., and H. S. Sack, Technical Development and Evaluation Center, Civil Aeronautics Administration, Indianapolis, Ind., Report No. 161, 8p. (Feb. 1952)

Preliminary models prove promising; further studies being made to improve operational characteristics, particularly sensitivity, when perfected, they can be used for compaction control, etc. in all types of earth construction, it takes 15 min. to take measurements and obtain results on complete set of density and moisture readings.

32. DETERMINING SOIL MOISTURE AND DENSITY BY NUCLEAR RADIATIONS. Lane, D. A., B. B. Torchinsky and J. W. T. Spinks (in "Symposium on the Use of Radioisotopes in Soil Mechanics"), ASTM Special Technical Publication 134, Pp. 23-34, (March 5, 1952) (Also: Engng. J., Montreal Vol. 36, No. 1, Pp. 1-7, (Jan. 1953)

The development of a meter which can be used to determine soil moisture and density is described. The moisture meter is based on fast neutron bombardment of the soil, causing reflection of slow neutrons which activate a detector foil. The activity of the detector foil after a given exposure time can be related to the water content of the soil. The density meter, using the same source and holder as the moisture meter, measures with a Geiger tube the gamma rays reflected by the mass of material through which they radiate. The zone of influence can be considered to be a sphere of about a 6-in. radius. Both the moisture meter and the density meter give a linear calibration.

Field testing of the moisture and density meters on sandy silt and medium plastic alluvial clays yield results which agree within 3% moisture, and most within 2% moisture, or less. Less accuracy was obtained when testing Bearpaw shale, the neutron meter indicating more moisture than is actually present. The presence of large amounts of organic material would also upset the calibration curve. Although considerable work is still necessary to determine the effect of these and other factors, results obtained in preliminary tests indicate that the neutron meter is of considerable practical value.

It is believed that, since soil-moisture determination is a major bottleneck in many aspects of engineering investigation, the development of new tools such as that indicated herein is most encouraging.

33. USE OF RADIOACTIVE MATERIAL TO MEASURE SOIL MOISTURE AND DENSITY. Belcher, D. J., et al., (in "Symposium on the Use of Radiiisotopes in Soil Mechanics"), ASTM Special Technical Publication 134 (March 5, 1952).

(Not seen)

34. DEVELOPMENT OF AN ALBRECHT TYPE METER FOR THE MEASUREMENT OF HEAT FLUX IN THE SOIL. Morse, B. B., Electrical Engineering Research Laboratory, Contract AF 19(604)-183, Scientific Report No. 4-01, Univ. of Texas, 43p. (May 30, 1952)

Discussion of a number of heat flow meters. The Albrecht design was found to be the most suitable for measurement in the soil. The instrument was improved using four Sanform rod thermistors horizontally one above the other. Three of the sensing elements were equipped with wire heated for the measurements of the thermal conductivity in situ. A detailed mechanical description is given. Only a few test measurements were made.

37. THE MEASUREMENT OF TEMPERATURE AND HEAT TRANSFER IN THE SOIL. Portman, J., Johns Hopkins Univ. Laboratory of Climatology, Publications in Climatology, Vol. 7, No. 2 Pp. 293-294, (1954)

The installation of soil thermometers, made as copper constantan thermojunctions, is described. In addition, a Gier and Dunkle heat flow plate now used to measure the heat transfer in the soil directly is described.

38. A TRANSIENT-FLOW METHOD FOR DETERMINATION OF THERMAL CONSTANTS OF INSULATING MATERIALS IN BULK. PART I - THEORY. Blackwell, J. H., J. appl. Phys., Vol. 25, No. 2, Pp. 137-144, (Feb. 1954)

This is a theoretical paper, largely mathematical, dealing with the computation of thermal conductivity from the time-temperature observations obtained from a thermal conductivity probe. A criticism of existing techniques of computation is given and a new equation is proposed, based on "short time" and "long time" combined solutions. This technique is intended to eliminate errors not accounted for in previous solutions, notably contact error.

The paper should be of interest to those who have followed the development of the thermal conductivity probe.

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39. IMPROVED MODELS OF THERMAL DIFFUSION IN THE SOIL. Lettau, H., American Geophysical Union. Transactions, Vol. 35, No. 1, Pp. 121-132, (Feb. 1954)

It is shown that the non-homogeneous case of soil-heat conduction, that is when soil-heat conductivity and capacity are functions of depth, can be treated rigorously. An exact formula is derived which gives the thermal diffusivity of the soil as a function of depth, on the basis of Fourier coefficients of diurnal courses of soil temperature at a variety of depths. By employment of the new model of soil-heat diffusion one avoids misleading results which are obtained when the classical model of heat diffusion in a solid conductor is applied to natural soil indiscriminately. The case of depth-time varying thermal diffusivity can only be solved in approximate form. The practical application of the classical and the two new models are discussed with the aid of soil temperature data obtained by the Johns Hopkins Laboratory of Climatology, Seabrook, N. J.

40. FINAL REPORT ON THE STUDY AND MEASUREMENT OF HEAT FLUX IN THE SOIL. Staley, R. C., B. E. Morse, K. Buettner and J. R. Gerhardt, Texas Univ. Electrical Engineering Research Laboratory, Contract AF 19(604)-183, Scientific Report, No. 4-02, 62p., (Sept. 30, 1954)

This report summarizes research activities dealing with the development and operation of an instrument for the direct measurement of heat transfer in the soil. The requirements of small physical size to avoid heat flow interference and of making measurements in situ so as to leave the soil undisturbed made it desirable to base such a design on an instrument originally developed by ALBRECHT. The final instrument uses wire wound resistance thermometers and, following a theoretical analysis of the heat transfer from various types of soil-imbedded heated elements, derives the in situ soil thermal conductivity from the temperature-time response of a single element rather than from a pair of elements. The construction and calibration of the heat flux meter are described. The results of a series of detailed measurements are presented along with a description of certain other measurements are presented along with a description of certain other measurements made during the Great Plains Turbulence Project at O'Neill, Nebraska. The data taken during this measurement project are given in a series of appendices. An evaluation of the reliability of the surface heat flux and soil thermal conductivity values show that in spite of satisfactory thermal conductivity values there is not at present a satisfactory technique for extrapolating sub-surface heat flux values to the surface. A brief description is also made of a portable hypodermic-type meter designed to measure the thermal conductivity of soil over small sensing volumes. A series of near surface thermal conductivities from 50 X 10^{-6} to 1400 X 10-6 cgs units.

41. ANALYSIS OF ERRORS IN GROUND AND AIR TEMPERATURE MEASUREMENTS. Rohsenow, W. M., J. A. Clark and P. C. Van Alstyne, U. S. Corps of Engineers. Frost Investigation, Report No. 4, 43p., (Oct. 1954)

This report is a discussion of various thermal errors associated with the measurement of ground and air temperatures. Errors associated with the digging of a pit and plunging temperature measuring devices into the ground through the side walls are considered. The effect of electric currents in resistance thermometers and in thermistors and the effect of radiation penetration in the ground are discussed. The types of errors associated with a long vertically installed temperature sensing unit are mentioned. Steady-state and transient errors associated with air temperature measurement under various conditions are presented.

42. AN EVALUATION OF TWO RAPID METHODS OF ASSESSING THE THERMAL RESISTIVITY OF SOIL. Makowski, M. W. and K. Mochlinski, Instn. Elect. Engrs., Proc. Paper 1942 M, Vol. 103, No. A, Pp. 453-70, (1955)

The methods are suitable for use in situ, with special application to the assessment of cable ratings. Brief consideration is given to the factors determining the thermal resistivity of the soil, i.e. its composition, compactness and moisture content, and then to the present standard method of measurement by buried spherical or cylindrical heater. The basis of the so-called transient-needle method is then set out. Theory, errors due to departure from ideal conditions and practical application are considered. A method based on soil sampling is next discussed. After critical considerations of the underlying theoretical

and practical work by Gemant, Kersten and Mickley in the United States, a nomogram is introduced by means of which the thermal resistivity of sand-clay mixtures of known physical characteristics may be simply determined. The practical application of the two rapid methods, to field measurements is described, and results obtained by the various methods are compared. Finally, the new methods are discussed and compared with that using the static buried heater.

43. "MEASUREMENTS OF SOIL MOISTURE AND DENSITY." U. S. Army, Corps of Engineers, (March 1955).

(Not seen)

44. SMALL PORTABLE METER FOR SOIL HEAT CONDUCTIVITY AND ITS USE IN THE O'NEILL TEST. Buettner, K., American Geophysical Union, Transactions, Vol. 36, No. 5, Pp. 827-830, (Oct. 1955)

A hypodermic needle is fitted, in its bore, with an electrical heating wire and a thermocouple. With certain precautions, its temperature increase yields data of soil heat conductivity. Very large local variations of the heat conductivity were found in the upper centimeters of the surface by this instrument at the U.S.A.F. Great Plains Turbulence Project at O'Neill, Nebraska, in 1953.

45. SOIL MOISTURE DETERMINATION BY A PORTABLE NEUTRON SCATTERING MOISTURE METER. Stone, J. G., D. Kirkham and A. A. Read, Soil Science Society of America, Proc. Vol. 19, No. 4, Pp 419-423, (Oct. 1955)

A portable battery powered device suitable for field measurements of soil moisture by neutron scattering is described. Except for the surface 6-9 in. the equipment generally gave the soil moisture per unit soil bulk volume within the range of the standard deviation of gravimetric determination. The equipment weighs 45 lbs. A simplified checking and standardization device is included.

46. EVALUATION OF SOIL HEAT CONDUCTIVITY WITH CYLINDRICAL TEST BODIES. Buettner, K., Am. Geophys Union Trans., Vol. 36, No. 5, Pp. 831-837 (Oct. 5, 1955)

Study relating to heated cylinders used as sensing elements to measure heat material constants in soil; different solutions for temperature increase with time of heated cylinder discussed; increase depends on cylinder geometry, heat conductivity of medium, and ratio of specific heats of cylinder and medium; for compact cylinders and not too fluffy media, increase is independent of heat capacity of medium.

47. ANALYSIS OF SOIL- AND AIR-TEMPERATURE DATA BY FOURIER TECHNIQUES. Carson, J. E. Argonne National Lab., Ill., Report 6398, Pp. 110-129, (1956)

Data for air temperature and soil temperatures at various depths at the Argonne site are presented for 1955. The annual cycles of air and soil temperatures for 1953 to 1955 are subjected to harmonic (Fourier) analysis, and the results are used to derive thermal diffusivities of the soil at various depths.

48. A CONTRIBUTION TO THE STUDY OF SOILS BY MEANS OF ELECTRICAL RESISTIVITY APPARATUS Bethlahmy, Nedavia
Doctoral Dissertation, Cornell Univ., 191p., (1956)

The Volusia-Mardin soil association, because of its poor drainage condition, constitutes a serious problem area in the southern New York plateau. An investigation was conducted to determine the applicability of the electrical resistivity method of geophysical exploration to a study of these soils. Data collected by the Wenner configuration, which consists of four equally spaced electrodes, and analyzed by superposition on standard curves yielded results pertaining to the depth of the substratum and the resistivity values of the several soil layers, and made possible the drawing of inferences with respect to subsurface flow of water. Volusia and Mardin soil series have strongly expressed fragipans. If soil moisture conditions are such that the res ulting resistivity curves can be interpreted by 2-layer standard curves, then the fragipan and overlying soil mass appear as one layer, while the substratum is the second layer. In such cases, the electrical resistivity method can be used only to determine the depth to the substratum. On the other hand, when soil moisture conditions are such as to require the use of 3-layer standard curves then the fragipan is differentiated from the overlying soil, and the method may be used both for depth determinations and resistivity evaluations.

Depth determinations by 2 and 3-layer curve analyses may be combined. Depth to the substratum was determined to be greater in Mardin soils than in neighboring Volusia soils Since the resistivity survey was combined with a topographic survey, conclusions could be drawn concerning the slope of the upper surface of the substratum Similar slopes were found under Mardin and nearby Volusia soils. This led to the conclusion that the surface of Mardin soils is at a higher elevation

than the surface of adjacent Volusia soils.

Resistivity analyses showed that the soil layers above the Volusia fragipan have a smaller resistivity value than their Mardin counterparts; that the fragipans of both soils have the same resistivity; and that the substrata of Mardin soils have resistivity values which are in some cases equal to, and at other times greater than the substrata resistivities of Volusia soils. These results led to inferences respecting the movement of water from one soil into the other. In wet periods, water flows horizontally over the fragipan from Mardin into Volusia soils. Some of the water flows downward through the permeable "gray streaks" in the Mardin fragipan until it reaches the substratum, where it again resumes a horizontal flow towards the Volusia substratum. Because the flowing water is confined between two impermeable strata, pressure may be built up, forcing water upwards through the "gray streaks" in the Volusia fragipan. A piezometric study in Volusia soil sites confirmed the presence of water under hydraulic pressure underneath the fragipan.

49. TENTATIVE METHOD OF TEST FOR THERMAL RESISTIVITY OF SOIL BY THE THERMAL PROBE. Winterkorn, H. F., AIEE Research Project on Soil Thermal Resistivity, First Annual Report, (July 1956)

(Not seen)

52. A PROBE FOR MEASUREMENT OF THERMAL CONDUCTIVITY OF FROZEN SOILS IN PLACE. Lachenbruch, A. H., Am. Geophys. Union Trans., Vol. 38, No. 5, Pp. 691-697, (1957)

Field measurement of thermal conductivity of non-metallic substances (such as frozen soils and ice) by the thermistor probe is presented and well illustrated. Accurate mathematical method for reduction of obtainable data is shown with numerous references, including the Van der Held and Van Drunen theory. The entire treatment is a competent and practical contribution to the urgent exploration and exploitation efforts in cold regions.

53. LOCAL VARIABILITY OF THERMAL CONDUCTIVITY-UNIVERSITY OF TEXAS. Buettner, K., (Pp. 46-49 in: Exploring the atmosphere's first mile, Lettau, H. H. and Ben Davidson, (editors), Vol. 1, N. Y., Pergamon Press, (1957)

The author describes the construction of the Buettner-Bahn portable λ-meter for determining soil thermal conductivity in situ. It "consists of a stainless steel hypodermic needle 2.5 cm long and 0.07 cm outside diameter. Inserted in the needle base with terminals in the base of the needle was a 2.5 cm loop of enameled resistance wire (total resistance 4.5 ohms) to be used as a heat source." The thermocouple principle was used as a thermal sensing device. A diagram of the instrument is presented. Its calibration is outlined and the method of measurement and the results obtained are discussed. A graph is given; showing the frequency distributions of 171 observations of soil thermal conductivity with the portable λ-meter at O'Neill, Nebr.

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54. SOIL DENSITY WATER CONTENT AND HEAT CAPACITY-JOHNS HOPKINS UNIVERSITY. Portman, D. J., (Pp. 41-45 in: Exploring the atmosphere's first mile, Lettau, H. H. and Ben Davidson, (eds.), Vol. 1, N. Y., Pergamon Press, (1957)

In connection with the measurements of soil density, water content and heat capacity made at the Johns Hopkins University site at O'Neill, Nebraska, the author discusses the methods employed to measure specific heat, namely its indirect measurement with the aid of equation: $C = C_w + C_d(1 - w)$, where C, C_w and C_d (cal $g^{-1}deg^{-1}$) are the specific heat of moist soil, water and dry soil, respectively, and W is the fraction of water by weight in moist soil; soil density by means of equation: $\rho = \rho_d(1 - W)$; and heat capacity using the computed specific heats and bulk densities. Tables giving specific heats of various soils (dry state) and estimated soil heat capacity at O'Neill, Nebraska, and graphs showing soil moisture and rainfall at O'Neill, Nebraska (1953) and dry density of soil at the same site are presented.

55. SOIL HEAT FLUX MEASUREMENTS. Staley, R. C. and J. R. Gerhardt, (Pp. 58-63 in: Exploring the atmosphere's first mile, Lettau, H. H. and Ben Davidson, (eds.),

The principles, advantages and disadvantages of the plate method and of the temperature gradient method for measuring heat flow are presented. This is followed by a presentation of the theory of the summation or "Temperature Integral Method" for evaluating surface soil heat flux by means of the equation:

$$S_o = (\rho c T\ )\, 0.5 + (\rho c \dot{T})\, 1.5 + \ldots (\rho c \dot{T})_D$$

The reduction of subsoil heat flux to surface values by the "Temperature Integral Method" involves the use of the relationship

$$\rho c \dot{T} = (\lambda T')' \approx \lambda T''$$

to convert from the ρc to the λ parameter assuming that $\lambda \approx 0$ and the equation

$$S_o = (\lambda T'')0 \text{ to } 1.0 + (\lambda T'')1.0 \text{ to } 2.0 + (\lambda T'')2.0$$

The soil surface heat flux values are given in Vol. 2

and the differences between the measurements of the University of Wisconsin and Johns Hopkins University values are discussed.

56. SOIL TEMPERATURE INSTRUMENTATION. Portman, D. J., (Pp. 17-18 in: Exploring the atmosphere's first mile, Lettau, H. H and Ben Davidson, Vol. I, N. Y. Pergamon Press, (1957)

Soil temperatures at various depths were measured during the Great Plains Field Program at O'Neill, Nebraska. Soil temperatures are important in studies of atmospheric turbulence because fluctuations in air flow near the ground are thermally as well as frictionally induced and the temperature of the soil surface is related closely to that of the air tempeature, they are important also in studying the role of temperature in the energy balance at the soil surface. Of the problems encountered in obtaining accurate soil temperature, the following are considered. Proper space sampling, placing of sensing elements at known depths with a minimum of disturbance to the natural soil conditions and instrumental accuracy. A table giving a summary of soil temperatures at O'Neill is included.

57. THERMAL CONDUCTIVITY-UNIVERSITY OF TEXAS. Buettner, K., (Pp. 29-38 in: Exploring the atmosphere's first mile, Lettau, H. H. and Ben Davidson, (eds.), Vol. 1, N. Y. Pergamon Press, (1957)

A brief description of the two element method of measurement of soil thermal conductivity *in situ* based upon an instrument designed by F. Albrecht and an account of its deficiencies is followed by a detailed discussion of the single element method, which involves the use of "one small cylindrically shaped element containing a thermal sensing element as a core and a spirally wound heater coil surrounding the thermometer."

The mathematical development of the single element method is presented and a description of the instrument a U-shaped Albrecht type flux meter, and of its circuitry is given with the aid of diagrams and a photograph. The instrumental error, the induction material, the possible heat conduction through the Bakelite frame and the characteristics of the data recorded (presented in Vol. 2) are discussed.

58. SOIL THERMOCOUPLES-JOHNS HOPKINS UNIVERSITY. Portman, D. J., (Pp. 19-20, in: Exploring the atmosphere's first mile, Lettau, H. H. and Ben Davidson, (eds.), Vol. 1, N. Y. Pergamon Press, (1957)

At the Johns Hopkins University site near O'Neill, soil temperatures were measured at depths 2.5-80 cm with copper-constantan thermojunctions. A description is given of the construction of the junctions for the various depths, the installation of the thermocouples and the heat flow plate (illustrated by means of a diagram) and the method of observation.

59. EMISSIVITY OF ICE, SNOW, AND FROZEN GROUND. Dunkle, R. V., J. T. Gier and J. T. Bevans, Refrig. Engng., Vol. 65, No. 4, Pp. 33-5, 89, (1957)

The measurement of the emissivity of snow, ice, and frozen ground was undertaken as a phase of a research program under the auspices of the Snow, Ice and Permafrost Research Establishment of the U. S. Army Corps of Engineers. The need for such information in environmental heat transfer studies is readily apparent and the results are of importance in many other fields of engineering.

60. ESTIMATION OF THE HEAT-TRANSFER COEFFICIENT BETWEEN AIR AND THE GROUND SURFACE. Scott, R. F., American Geophysical Union, Transactions, Vol. 38, No. 1, Pp. 25-32, (Feb. 1957)

For the purposes of programming a computer to predict the depths of freezing and thawing in soils, a simple method is outlined with the appropriate charts for calculating the value of the surface heat-transfer coefficient, based on meteorological information which is normally easily obtainable. All the significant parameters are included, and an account of the investigation leading to the preparation of each chart is given.

61. "A GAMMA SCATTERING SOIL DENSITY GAUGE FOR SUB-SURFACE MEASUREMENTS." Cameron, J. F. and M. S. Bourne, Internat. J. Applied Radiation and Isotopes, Vol. 3, Pp. 15-19, (1958)

A gauge for *in situ* measurements of soil densities with an accuracy of about 1 percent which can be used at depths down to 1000 ft. is described. A caesium-137 γ-ray source is separated by a cylindrical lead shield from a Geiger counter which detects the γ-radiation scattered by the soil. The optimum source-detector spacing is experimentally determined. Pulses from the Geiger counter are fed along a cable to the scaling unit by means of a transformer impedance-matching circuit. A complete design and the method of calibration is given.

62. "METHOD OF MEASUREMENT OF THE REAL THERMAL DIFFUSIVITY OF MOIST SOIL." Jackson, R. D. and D. Kirkham, Soil Soc. Amer. Proc., Vol. 22, No. 6, Pp. 479-482, (Nov. Dec., 1958)

To get away from thermally induced errors in soil diffusivity measurements, an alternating heat source was used to allow moisture transfer in alternate directions (thus reducing diffusivity at decreasingly smaller periods (with corresponding smaller temperature gradients) of the alternating heat source. These results plotted on a curve which can be extrapolated to zero period gives a value of diffusivity (real diffusivity) for zero temperature gradient. This method was used on samples of clay loam and sand at a number of moisture contents and tensions. The diffusivities increase steadily as moisture increases to saturation. This differs from former results showing maxima at $<$ saturation. These maxima occur in apparent and real diffusivities.

63. ON THE CYLINDRICAL PROBE OF MEASURING THERMAL CONDUCTIVITY WITH SPECIAL REFERENCE TO SOILS. I. EXTENSION OF THEORY AND DISCUSSION OF PROBE CHARACTERISTICS. DeVries, D. A. and A. J. Peck, Austral. J. Phys., Vol. 11, No. 2, Pp. 255-271, (1958)

Authors present an extension of the theory of cylindrical probes of infinite thermal conductivity for nonstationary thermal conductivity measurements of soils and materials of similar thermal properties to the case of a homogeneous probe of finite conductivity with a line source of heat at its center. An analysis of experimental results made on the basis of this extended theory shows that deviations from the simple theory of a probe of infinite conductivity are negligible if the outer probe diameter and the probe length are of the order of 0.1 cm or less and 10 cm, respectively, and if the thermal conductivity of the probe is large in comparison with that of the observed material, and if the volumetric heat capacities of both are nearly equal. It is shown how an estimate can be made of the influence of the contact resistance between the probe and the observed material on the thermal conductivity of the latter. A negligibly small or accurately known contact resistance makes it possible to find the thermal diffusivity of the investigated material but no remarkable accuracy is to be expected.

64. ON THE CYLINDRICAL PROBE METHOD OF MEASURING THERMAL CONDUCTIVITY WITH SPECIAL REFERENCE TO SOILS. II. ANALYSIS OF MOISTURE EFFECTS. DeVries, D. A., and A. J. Peck, Austral. J. Phys., Vol. 11, No. 3, Pp. 409-423, (1958)

Effects of uneven moisture distribution caused by temperature gradients and gravity on nonstationary thermal conductivity measurements of unsaturated porous materials by means of cylindrical probes are discussed. An analysis of simplified equations for simultaneous transfer of heat and moisture shows that temperature gradients produce a decrease of moisture content at the probe surface which is approximately inversely proportional to the radius of the probe, and increases with increasing time and temperature. For most soils the redistribution of moisture and its effects on the measured temperature rise will be insignificant at average temperatures below about 40°C for a probe diameter of 0.1 cm, a heating time of the order of 100 sec, and a temperature rise at the probe surface of less than 1°C. The effect of variation of moisture content in the vertical direction due to gravity also is usually negligible. The importance of measuring both the heating and cooling branch of the temperature-time relation in detecting the influence of moisture redistribution is illustrated.

65. A STUDY OF THE SUPERPOSITION OF HEAT FIELDS AND THE KENNELLY FORMULA AS APPLIED TO UNDERGROUND CABLE SYSTEMS. Bauer, C. A. and R. J. Nease, AIEE Transactions, Vol. 76, Pt. III, Pp. 1330-37, (Feb. 1958)

Tests on applicability of Kennelly formula to underground cables; final ground temperature at any point in heat field can be calculated using Kennelly formula and adding to this measured or calculated value of ambient ground temperature at given depth.

66. A GRAPHICAL TECHNIQUE FOR DETERMINING EVAPOTRANSPIRATION BY THE THORNTHWAITE METHOD. Palmer, W. C. and A. V. Havens, Monthly Weather Review, U. S. Weather Bureau, Washington, D. C., Vol. 86, Pp. 123-28, (April 1958)

Prepared for the Weather Bureau short course in Agricultural Meteorology, July 1956. 3 sheets 35 x 47 cm. 2 charts. Nomograms and instructions for their use in climatology are presented.

67. SUGGESTED METHOD OF TEST FOR THERMAL RESISTIVITY OF SOIL BY THE THERMAL PROBE. Procedures for Testing Soils, American Society for Testing Materials, Pp. 179-85 (April 1958)

(Not seen)

70. PERIODIC HEAT FLOW IN A STRATIFIED MEDIUM WITH APPLICATION TO PERMAFROST PROBLEMS. Lachenbruch, A. H., Geological Survey Bulletin No. 1083-A, 35p., (1959)

Solutions to the Fourier heat equation for quasi-steady periodic flow in a stratified semi-infinite medium can be obtained readily by standard methods. The results have wide application to studies of earth-temperature variations induced by diurnal, annual, and other periodic variations. One application is to the important problem of determining the minimum thickness of gravel fill required to maintain the material on which it rests (the subgrade) in a perennially frozen state in permafrost areas. The results indicate that the required fill thickness is very sensitive to the thermal properties of the subgrade. If a thin layer of material with a low thermal contact coefficient, such as spruce logs, is placed between the fill and subgrade, the thickness of fill required to maintain undisturbed permafrost can be greatly reduced. The thermal properties of the soil beneath the layer supporting plant growth can have an important influence on the temperatures in that layer. This effect is likely to have important application to plant ecology in the arctic. The theory yields an approximate method of estimating the effect of winter snow cover on the mean annual temperature of the ground surface.